

BOREHOLE GEOPHYSICS

After the well has been drilled, the cuttings have been analyzed and described, the drill-time/lithology log has been completed, the open, non-cased borehole provides an excellent access to the ground-water system at a single point. Borehole geophysical investigations provide excellent vertical-profile information on the lithology, flow components (production zones), structure, permeability, porosity, and water quality of the ground-water system. Multiple logs typically are collected to take advantage of their synergistic value: much more can be learned from a suite of logs than from individual analysis of the same logs. Geophysical logs provide unbiased, continuous and in-situ data and generally sample a larger volume than drilling samples.

Simply put, downhole measurements are taken with an electrically-powered probe connected to a cable with one or more conductors. Electrical voltage and data pulses are transmitted through the cable to and from a surface recording device. The surface equipment usually consists of a drawworks, depth encoder, power supply, series of electronic panels, computer, and an output device, such as a printer, monitor, or pen recorder. The probe is hoisted up or down the borehole at a constant speed while data are being sent to the surface and recorded. All also are recorded with depth, creating curves of borehole measurements. Some logging devices produce digital "pictures" of the borehole wall or measurements of vertical flow rates in the borehole.

Borehole geophysical logging techniques were developed in the petroleum industry, but the techniques and equipment have been modified or developed for the ground-water industry. A basic, portable, tuck-mounted system appropriate for most ground-water investigations can cost \$5,000-\$10,000. Commercial petroleum loggers may charge \$3,000 for two logs.

Surface geophysical techniques also have very useful applications to ground-water investigations, including determination of the depth and distribution of lithologic units, depth to ground water, presence and distribution of certain contaminants, buried objects (tanks), and land disturbances (cavities, reworked soils, edges of landfills, etc.) These techniques will only be briefly discussed in this course.

References:

- Keys, W. Scott and MacCary, L.M., 1990, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations of the United States Geological Survey, Book 2, Chapter E1. 126 p.
- Driscoll, F.G., 1987, Groundwater and wells: Johnson Division, St. Paul, Mn., 1089 p.
- Paillet, F.L. and Williams, J.H., 1994, Proceedings of the U.S. Geological Survey workshop on the applications of borehole geophysics to ground-water investigations, Albany, New, York, June 2-4, 1992: U.S. Geological Survey Water-Resources Investigations Report 94-4103. 79 p.

Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1990, Application of surface geophysics to ground-water investigations: U.S. Geological Survey Techniques of Water-Resources Investigations of the United States Geological Survey, Book2, Chapter D1, 116 p.

WHY LOG?

- Delineation of hydrogeologic units
- Definition of ground-water quality
- Determination of well construction and conditions

TYPES OF LOGS

- Caliper logs
- Natural-gamma logs
- Single-point resistance logs
- Spontaneous-potential logs
- Normal-resistivity logs
- Electromagnetic-induction logs
- Fluid-resistivity logs
- Temperature logs
- Flowmeter logs (velocity measurements)
- Television logs
- Acoustic-televiwer logs

Table 1.--Logging techniques with application to waste disposal			
Type of Log	How the probe functions	Parameters recorded or inferred	Required hole conditions
Acoustic Velocity (full wave recording)	Acoustic pulses generated by transducer(s) in the sonde are sensed by receivers along the length on the sonde.	Compressional or shear wave transit time--porosity, amplitude, attenuation, cement bond--full wave form, moduli of elasticity.	Uncased, liquid filled
Acoustic Televiwer	An acoustic transmitter--receiver is rotated to scan reflection from the wall of the borehole and oriented on magnetic north.	Location and orientation of fractures and solution openings.	Uncased, liquid filled
Caliper	3-4 pads, bow springs or feelers that follow the wall of the hole.	Hole diameter, location of fractures and solution openings. Correlation of hole features with borehole televiwer and other logs.	Cased or uncased, air or liquid filled
Casing Inspection	Differences in steel casing causes changes in the magnetic field surrounding an electromagnet in the probe.	Location of collars, joints, screens and corroded sections.	Cased, liquid or air filled
Flowmeter	Impeller--the revolution rate is measured. Tracer--the movement of a tracer is timed between and injector and a detector.	Vertical components of flow in a single well.	Cased or uncased
Fluid Conductivity	Voltage drop across several ring type electrodes in a tube is related to resistance or conductance of the fluid moving through the probe.	Provides a measurement of the conductivity of the liquid in the borehole.	Cased or uncased, filled with water or water-base mud
Gamma, Natural	A detector measures gross gamma activity of naturally occurring and artificial radioisotopes.	Useful for identification of lithology and stratigraphic correlation. Increases in clay or shale content usually cause higher gamma radiation in sediments.	Cased or uncased, liquid or air filled
Gamma Spectrometry	Gamma photons from both natural and artificial radioisotopes have characteristic energies. The spectral probe transmits energy dependent pulses.	Measures the distribution of potassium, uranium, and thorium. Stratigraphic correlation and identification of lithology. Identification of artificial radioisotopes near radioactive waste disposal sites.	Cased or uncased, liquid or air filled
Gamma-Gamma	Contains a gamma source shielded from a detector. The backscattered and attenuated gamma radiation is a function of the electron density of the material within the borehole and surrounding rocks.	Estimation of bulk density and porosity. Identification of lithology and the location of cavities and cement between the casing and borehole wall.	Cased or uncased, liquid or air filled

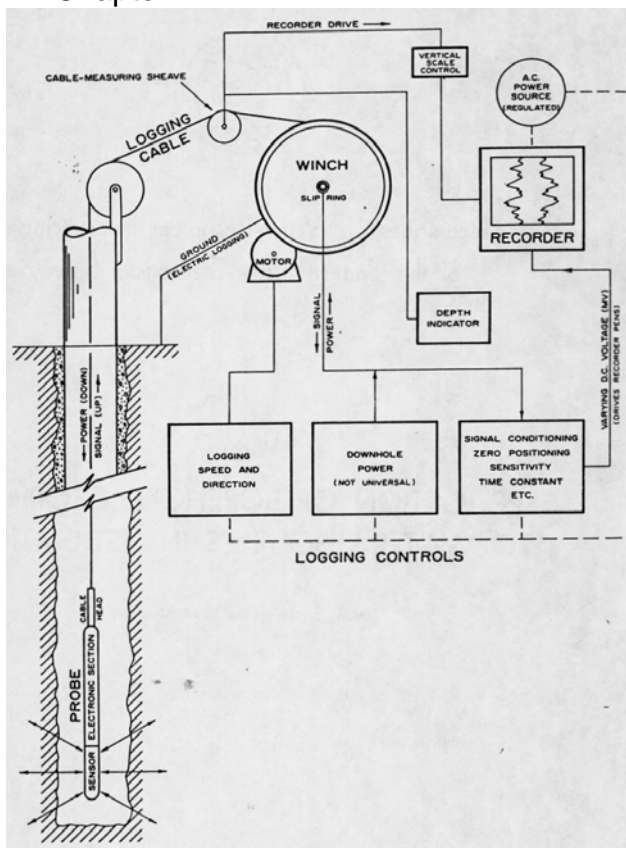
Table – Types of geophysical tools and their application to ground-water studies.

Table 1.--Logging techniques with application to waste disposal--continued.

Type of Log	How the probe functions	Parameters recorded or inferred	Required hole conditions
Neutron	Neutrons from a source are moderated by hydrogen atoms in the borehole and surrounding rocks between a source and detector.	Responds to porosity below the water table and moisture content above the water table. Also related to lithology.	Cased or uncased, liquid or air filled
Resistivity and Induction	The voltage drop between electrodes on the sonde is a function of the resistivity of the formation and fluid in the hole. Numerous configurations and spacings are available for different applications. Coils are used for induction logging.	Measures the apparent resistivity of a volume of rock adjacent to the borehole. Formation water saturation, formation resistivity factor, and R_M may be calculated. Lithology and stratigraphic correlation of aquifers.	Uncased, filled with water or water-base mud for electrode devices. No fluid necessary for induction logging
Single Point	The point resistance sonde measures resistance between an electrode in the hole and an electrode at the surface.	Stratigraphic correlation, location of bed boundaries, changes in lithology and location of fractures in resistive rocks. Non-quantitative.	Uncased, filled with conductive liquid
Spontaneous Potential	Measures the difference in electrical potential between a moving borehole electrode and an electrode at the surface	Lithology, stratigraphic correlation, water resistivity, clay or shale content, zones of water-inflow.	Uncased, filled with conductive liquid
Temperature	Changes in resistance of a thermistor or platinum sensor are measured.	Source and movement of water in a well. Geothermal gradient. Correct fluid resistivity for electric logs.	Cased or uncased, liquid-filled
Water Sampler	A motor is activated from the surface to open and close a valve at a predetermined depth.	Water samples may be taken from preselected depths for laboratory analysis.	Cased or uncased, water filled

Table -- Types of geophysical tools and their application to ground-water studies--continued

GROUND-WATER-DATA COLLECTION



**ELECTROMAGNETIC CONDUCTIVITY,
IN MICROSIEMENS PER CENTIMETER**

0 200 400 600 800 1000

DEPTH, IN METERS BELOW LAND SURFACE

0 200 400 600 800 1000

WATER TABLE

FINE SAND

FINE TO MEDIUM SAND

GEONICS EM39 LOG MARCH 1991

FINE SAND

FINE TO MEDIUM SAND

CENTURY 9510 LOG APRIL 1992

VERY FINE TO FINE SAND

FINE SAND

VERY FINE TO FINE SAND WITH SOME SILT AND CLAY

FINE SAND

GEOELECTRIC INTERPRETATION MODEL

WELL A523

MARCH 1991
4250 $\mu\text{S}/\text{CM}$

APRIL 1992
4100 $\mu\text{S}/\text{CM}$

SCREENED INTERVAL

INTERPRETED LOG

WELL A524

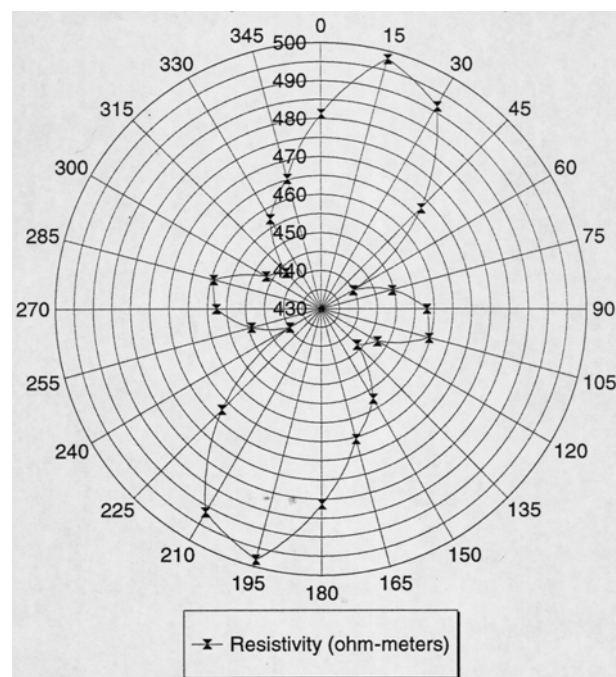
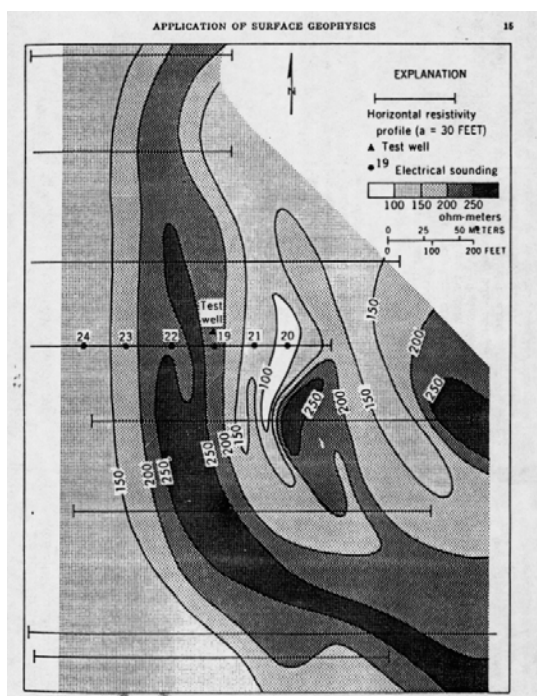
MARCH 1991
192 $\mu\text{S}/\text{CM}$

APRIL 1992
193 $\mu\text{S}/\text{CM}$

SCREENED INTERVAL

Figures – Electromagnetic-induction and lithologic logs, specific conductance of ground water, and geoelectric section for a monitoring-well pair (above).

Example of square-array resistivity survey (below).



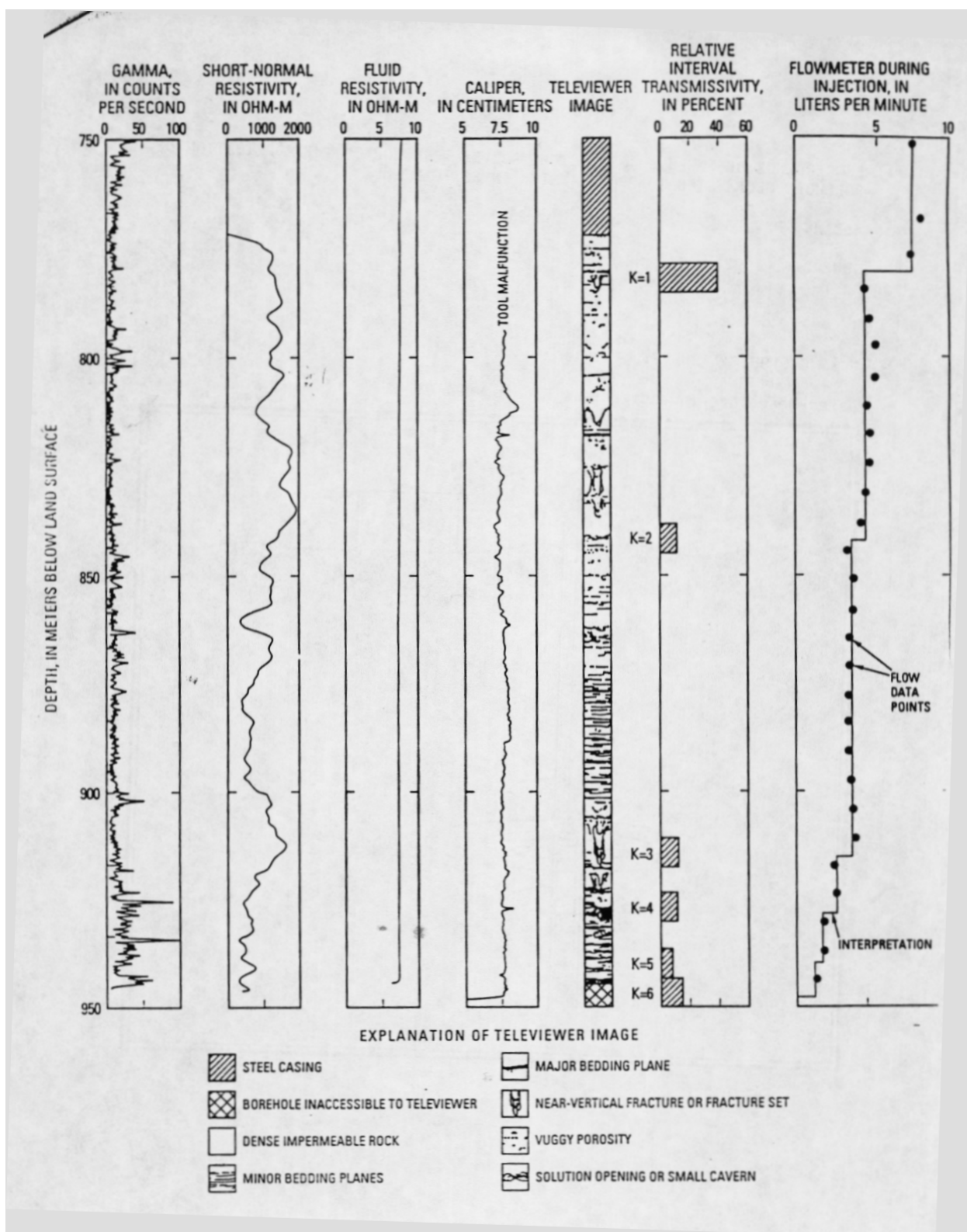


Figure – Suite of geophysical logs from a fractured-bedrock borehole.

GROUND-WATER-VELOCITY MEASUREMENT (TOOLS and TECHNIQUES)

Several geophysical (downhole) tools are available for the measurement of ground-water velocity in boreholes or wells. In addition to the tools there are various other techniques that can be used for the measurement of ground-water-flow rates. Such techniques may include injection/tracer tests. Most methods determine vertical flow rates.

Technique	Physical principle	Application	Reference
Conventional well logs			
Temperature	Passive tracer	Vertical flow	Keys (1990) Keys and Brown(1978)
Fluid resistivity or conductivity probe	Passive tracer	Vertical flow	Paillet (1991) Keys (1990)
Impeller flowmeter	Flow turns impeller	Vertical flow	Keys (1990) Keys and Sullivan (1979) Schimschal (1981)
Brine injection	Tag/trace with ions	Vertical flow	Patten and Bennett (1962)
Thermal-pulse flowmeter	Tag/trace with heat pulse	Vertical or horizontal	Hess (1986) Hess and Paillet (1990) Kerfoot (1988)
Hydrophysical logging	Replace fluid and monitor conductivity	Vertical flow	Tsang and others (1990)
Electromagnetic flowmeter	Currents induced by flow through generator	Vertical flow	Young and Waldrop (1989) Molz and Young (1993)
Laser doppler flowmeter	Doppler shift of reflected laser	Vertical or horizontal	Momii and others (1993)
Acoustic doppler flowmeter	Doppler shift of acoustic beam	Vertical flow behind casing	Rambow (1991)
Active listening	Movement of scattering pattern	Vertical flow behind casing	Rambow (1991)

Table – Summary of high-resolution borehole-flow and related measurement techniques.

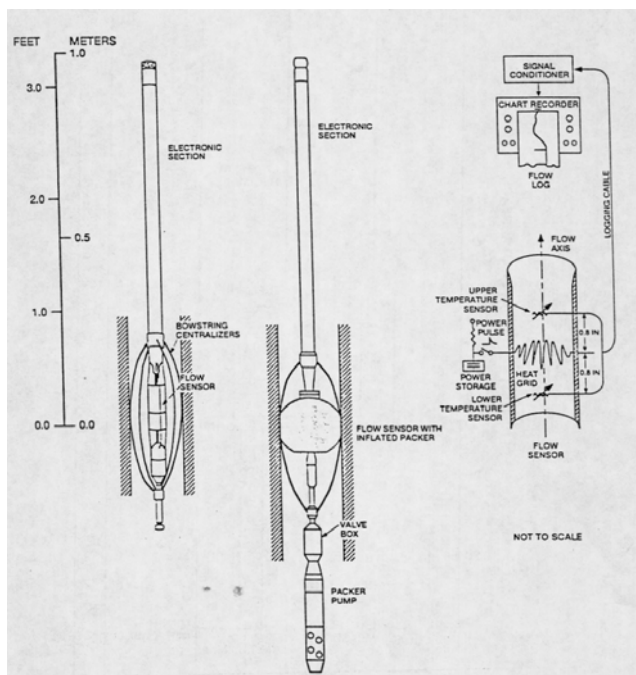


Figure – Borehole heat-pulse flowmeter
Measures vertical flow.

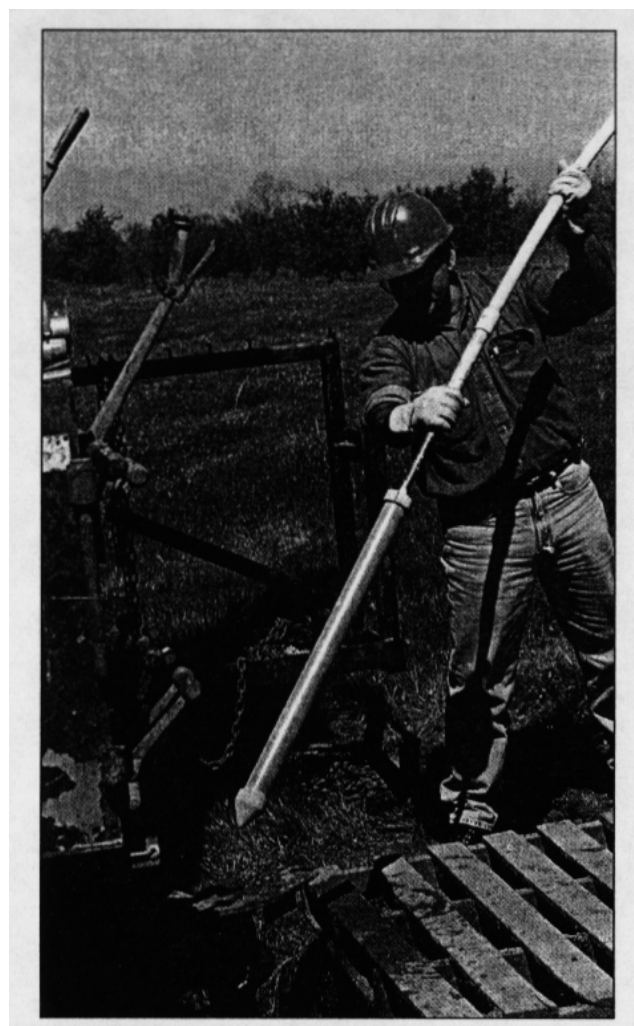


Figure – In-situ ground-water flow-velocity tool. Measures 3-dimensional flow field

TRACER TESTS

Tracer tests involve emplacing a tracer (conservative substance that mixes with the ground water) in a monitoring well and documenting the movement of the tracer in the aquifer around the injection well, or between two or more wells, over a period of time. Tracer tests can be used to document flow paths, determine ground-water-flow velocities and provide contaminant-transport parameters.

Any hazardous-waste site that involves ground-water contamination can be considered a tracer test. Generally, however, we have no control over the rate of injection.

Unlike most other ground-water characterization techniques, the tracer test usually provides direct information on the ground-water flow paths and velocities. However, the tests are seldom used because of the costs involved, the general reluctance to inject additional constituents into ground-water contamination sites, and the difficulty in completing the tests.

TYPES OF TRACER TESTS

- Single Well
 - Injection/Withdrawal
 - Borehole Dilution

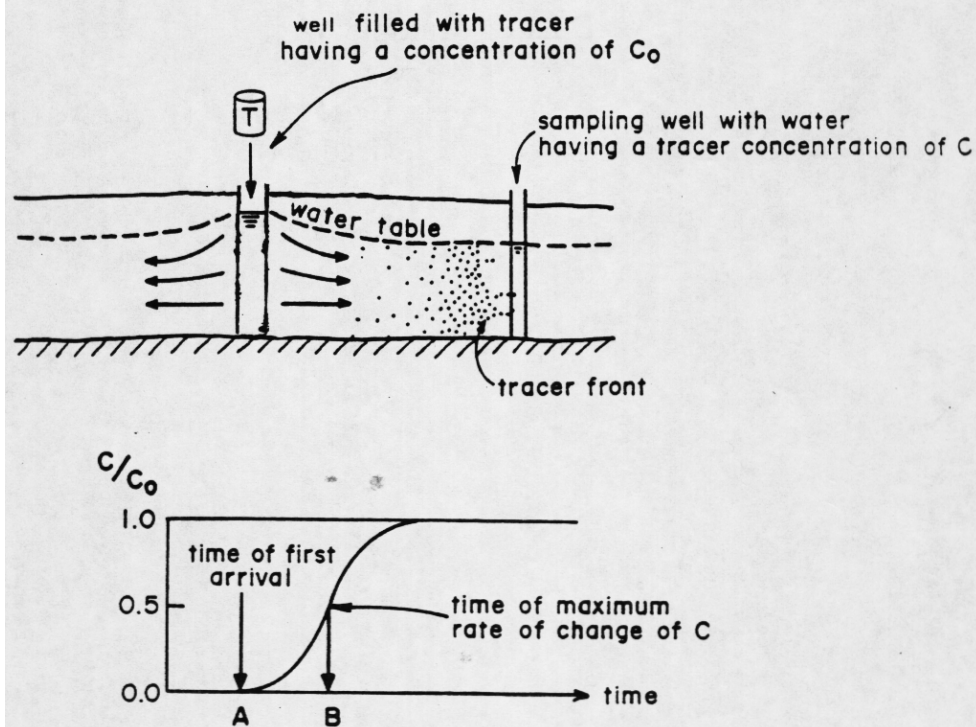
Measure aquifer characteristics near the borehole, but very little beyond a few feet. These tests are generally easier to implement than multiple-well tests.
- Dual or Multiple Well
 - Uniform (Natural Gradient)
 - Radial flow

Measure aquifer characteristics in the area between the well tests. Usually the further away the wells, the more tracer is lost to the system, and the harder the interpretation.

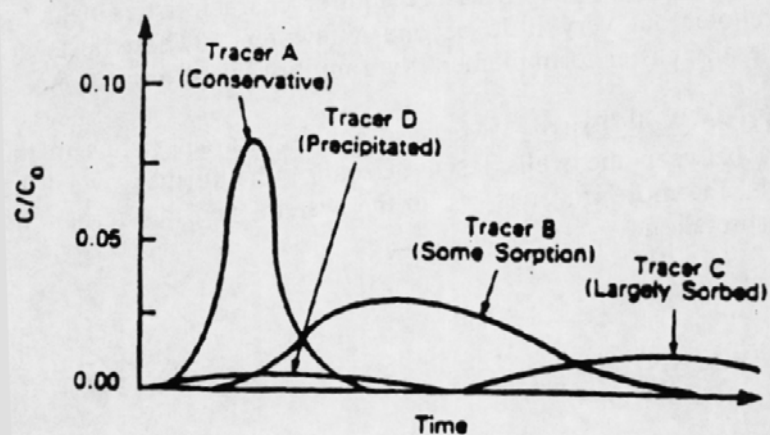
TYPES OF TRACERS

NATURAL TRACERS			INJECTED TRACERS			
Stable Isotopes		Radioactive	Activatable		Inactive	
					Ionized	Drift Material
Deuterium	2H	Tritium 3H	Bromide	35Br	Salts: Na+CL-	Lycopodium spores
Oxygen—18		Sodium—24	Indium	49In	K+Cl-	Bacteria
Carbon—13		Chromium—51	Manganese	25Mn	Li+Cl-	Viruses
Nitrogen—15		Cobalt—58	Lanthanum	57La	Na+I-	Fungi
Strontium—88		Cobalt—60	Dysprosium	66Dy	K+Br-	Sawdust
Radioactive Isotopes			Fluorescent Dyes			
Tritium	3H	Gold—198	<u>Optical Brightners</u>			
Carbon—14		Iodine—131	Direct Yellow 96			
Silicon—32		Phosphorous—32	Fluorescein			
Chlorine—36			Acid Yellow 7			
Argon—37			Rhodamine WT			
Argon—39			Eosin (Acid Red 87)			
Krypton—81			Amidorhodamine (Acid Red 50)			
Drypton—85			<u>Physical Characteristics</u>			
			Water Temperature			
			Flood Pulse			

Conceptual Diagram of a Two-Well Tracer Test



BREAKTHROUGH CURVES FOR DIFFERENT TYPES OF TRACERS



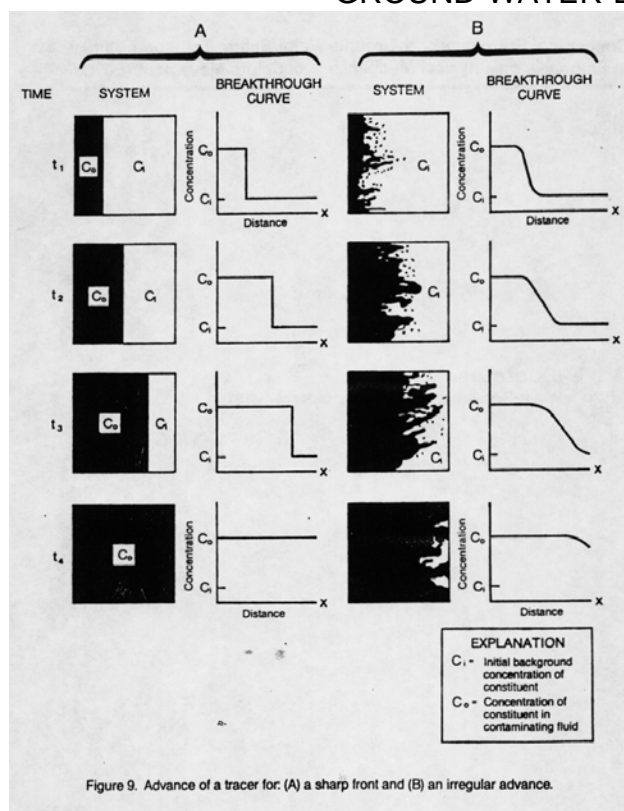


Figure 9. Advance of a tracer for: (A) a sharp front and (B) an irregular advance.

Figure – Typical irregular breakthrough curve.

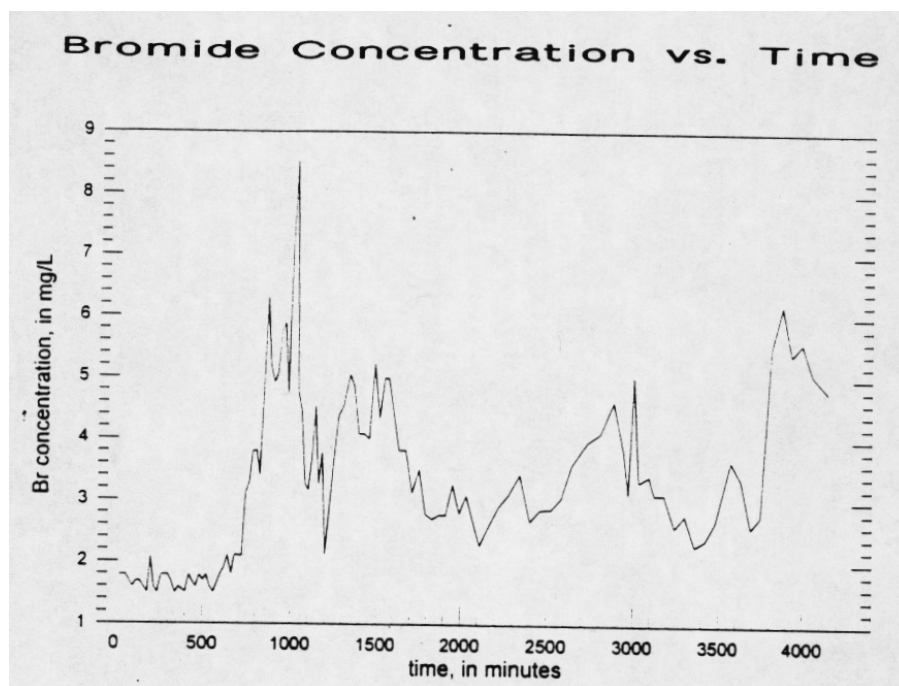


Figure – Actual test. Unfortunately most tracer tests don't perform as intended (note multiple breakthroughs).